

Interferometric detections of GOODS 850-5 at 1 mm and 1.4 GHz¹

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ABSTRACT

We have obtained a position (at sub-arcsecond accuracy) of the submillimeter bright source GOODS 850-5 (also known as GN10) in the GOODS North field using the IRAM Plateau de Bure interferometer at 1.25 mm wavelengths (MM J123633+6214.1, flux density: $S_{1.25\text{ mm}} = 5.0 \pm 1.0$ mJy). This source has no optical counterpart in deep ACS imaging down to a limiting magnitude of $i_{775} = 28.4$ mag and its position is coincident with the position found in recent sub-millimeter mapping obtained at the SMA (Wang et al. 2007). Using deep VLA imaging at 20 cm, we find a radio source ($S_{20\text{ cm}} = 32.7 \pm 4.3$ μ Jy) at the same position that is significantly brighter than reported in Wang et al. The source is detected by Spitzer in IRAC as well as at 24 μ m. We apply different photometric redshift estimators using measurements of the dusty, mid/far-infrared part of the SED and derive a redshift $z \sim 4$. Given our detection in the millimeter and radio we consider a significantly higher redshift (e.g., $z \sim 6$ Wang et al. 2007) unlikely. MM J123633+6214.1 alias GOODS 850-5 nevertheless constitutes a bright representative of the high-redshift tail of the submillimeter galaxy

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population that may contribute a significant fraction to the (sub)millimeter background.

Subject headings: Galaxies: formation — Galaxies: high-redshift — Galaxies: starburst — Galaxies: individual (MM J123633+6214.1) — Infrared: galaxies — Submillimeter

1. Introduction

Research in the last decade showed that to understand the assembly and formation of massive galaxies it is critical to study Submillimeter Galaxies (SMGs; see Blain et al. 2002, for a review). Since their first detection ten years ago (Smail et al. 1997), more than three hundred dust-enshrouded high- z objects ($z > 2$) have been detected by SCUBA and by MAMBO in the submillimeter and millimeter regime (e.g., Hughes et al. 1998; Bertoldi et al. 2000; Dannerbauer et al. 2002, 2004; Smail et al. 2002; Greve et al. 2004; Wang et al. 2004; Pope et al. 2006; Coppin et al. 2006; Bertoldi et al. 2007). Due to the large beam size in the (sub)mm (SCUBA: $15''$, MAMBO: $11''$), it is impossible to do a proper identification in other wavebands (such as the optical and near-infrared) based on bolometer data only. Thus, typically interferometric observations at radio wavelength with the VLA were used to identify the location of the SMGs, yielding a radio identification rate of $\sim 50 - 70\%$ (e.g., Smail et al. 2000; Dannerbauer et al. 2004; Wang et al. 2004; Pope et al. 2006; Ivison et al. 2007), depending on both the depths of the radio and the bolometer maps. The main drawback of this technique is, however, that the radio flux is redshift dependent, whereas the (sub)mm flux density at $z \geq 1$ is not (due to the inverse K correction; e.g., Blain & Longair 1993): one would thus expect the highest redshift ($z > 3$) sources (e.g., Barger et al. 2000) to be very faint at radio wavelengths if they were to follow the radio-FIR correlation (e.g., Condon 1992). We note that the radio-identified SMG with the highest redshift lies at $z \sim 3.6$ (Chapman et al. 2003, 2005). Based on this sample, CO observations of radio identified SMGs (e.g., Neri et al. 2003; Genzel et al. 2003; Greve et al. 2005) lead to the main conclusion that SMGs are massive galaxies in formation and Chapman et al. (2005) argue that the contribution to the star-formation rate density (SFRD) from this population is missed by UV-selected surveys. If one only uses radio-identified sources (e.g., Chapman et al. 2003, 2005) one thus has to be aware of the fact that the radio selection introduces a bias towards the low end of the true redshift distribution. To summarize, our knowledge about the nature and properties of the SMG population is mainly based on radio-identified SMGs — a biased sample.

One of the open questions in the investigations of SMGs is if there exists a signifi-

cant very high-redshift tail ($z > 4$; e.g., Dannerbauer et al. 2002, 2004; Valiante et al. 2007; Younger et al. 2007). The existence of such a tail would not be in contradiction to constraints from measurements of the cosmic infrared background (Gispert et al. 2000). Interferometric observations in the (sub)mm hold the promise to locate the positions of bright SMGs to sub-arcsec accuracy. One of the brightest SCUBA sources in the GOODS North field is GOODS 850-5 (Wang et al. 2004; this source is labeled GN 10 in Pope et al. 2005¹) with a submm flux $S_{850\ \mu m} = 12.94 \pm 2.14$ mJy (Wang et al. 2004)². Until very recently this bright SMG did not have a known counterpart which motivated observations with the IRAM Plateau de Bure Interferometer (PdBI; Guilloteau et al. 1992) to obtain an accurate position for this source. In the meanwhile, Wang et al. (2007) reported the location of GOODS 850-5 through SMA observations. Based on their detection in the submm (and subsequent identification in IR observations) and a $2\ \sigma$ detection in the radio ($S_{1.4\ GHz} = 18.7 \pm 8.6\ \mu\text{Jy}$), Wang et al. (2007) argue that the redshift of GOODS 850-5 is $z > 4$ and could even lie between $z = 5.6 - 8.0$ - with a much lower probability at $z < 4.5$.

Here we report the results based on our PdBI observations. We adopt the cosmological parameters $\Omega_{matter} = 0.27$, $\Omega_{\Lambda} = 0.73$, and $H_0 = 71\ km\ s^{-1}\ Mpc^{-1}$ (Spergel et al. 2003, 2007). Furthermore, we assume a Salpeter initial mass function from 0.1 to 100 M_{\odot} . We use the AB magnitude scale (Oke & Gunn 1983).

2. Observations

The final map resulting from our observations between December 2005 and August 2006 with the Plateau de Bure millimeter interferometer in C and D configuration are based on 6.8 hours of on-source observing time. The phase center (see Table 1) was set at the nominal SCUBA position published in Wang et al. (2004). The source was observed in the 1 mm and 3 mm band simultaneously. The 1 mm receiver was tuned at 240.000 GHz (corresponding to 1.25 mm) to obtain an accurate position. The 3 mm receiver was tuned to 98.3188 GHz, i.e., the frequency of the CO(2-1) transition redshifted to $z = 1.3448$. This is the redshift of the optical source GOODS850-5a (Wang et al. 2004) which is situated close ($\sim 2.4''$) to the SCUBA bolometer position. The total bandwidth of 580 MHz covers a redshift space of $\Delta z = 0.0138$ at that redshift (i.e. within the redshift uncertainty of the source, cf: $z = 1.344$ in Cohen et al. 2000 and Pope et al. 2006; $z = 1.345$ in Wang et al. 2004; $z = 1.34476$ in Wirth et al. 2004).

¹The distance between these two positions is $2.8''$, i.e. within the SCUBA bolometer position uncertainties.

²Pope et al. (2005) report $S_{850\ \mu m} = 11.3 \pm 1.6$ mJy

The data were calibrated through observations of standard bandpass (3C273, J0418+380), phase/amplitude (1044+719, 1150+497) and flux calibrators (CRL 618, 3C273, 1044+719, 1150+497) and reduced with the GILDAS software packages CLIC and MAP. The FWHM of the beam is $1.4'' \times 1.1''$ at 240 GHz and $3.4'' \times 3.2''$ at 98.3 GHz.

We detected the dust continuum emission of GOODS 850-5 at 5σ significance at $S_{1.25\text{ mm}} = 5.0 \pm 1.0$ mJy. The derived position is RA(J2000)=12:36:33.45, DEC(J2000)=62:14:08.95 (hereafter: MM J123633+6214.1) with an estimated position uncertainty of $\pm 0.3''$. The position and flux density of MM J123633+6214.1 are derived from point source fits of the visibilities in the UV plane and are consistent with the values derived in the image plane. The difference between the SCUBA (Wang et al. 2004) and our millimeter interferometric position is only $-0.02''$ in RA and $-0.48''$ in DEC, and our position is consistent with the SMA position from Wang et al. (2007), see summary in Table 1. In the 3 mm band no line was detected down to a rms of 0.8 mJy beam^{-1} (channel width: 40 MHz, 120 km s^{-1}) on the position of the optical source at $z = 1.3448$ (and also at the position of GOODS 850-5). This corresponds to an upper limit (3σ) of the integrated flux intensity of 1.2 Jy km s^{-1} , adopting a typical CO width for a SMG of 500 km s^{-1} (e.g., Greve et al. 2005). However, we note that a number of CO detections of SMGs have even lower integrated flux intensities than this 3σ upper limit (e.g., Greve et al. 2005).

We have used new, deep VLA radio continuum observations (Morrison et al. 2008) to constrain the radio flux density of GOODS 850-5. These observations reveal a highly significant radio source ($S_{1.4\text{ GHz}} = 32.7 \pm 4.3\text{ }\mu\text{Jy}$); i.e. a source that is significantly brighter than the upper limit reported in Wang et al. (2007). Our derived flux density is however in agreement with the 3σ detection reported in Pope et al. (2006). The radio emission is unresolved with a FWHM $\sim 1.7''$.

In our analysis, we use the exquisite multi-wavelength dataset available for the GOODS North field (e.g., Alexander et al. 2003; Giavalisco et al. 2004; Dickinson et al., in preparation) and have corrected these data products for the offset of $-0.38''$ in declination between VLA and the GOODS imaging products (see also Pope et al. 2006).

3. Discussion

3.1. Multi-wavelength Properties of MM J123633+6214.1 alias GOODS 850-5

The PdBI/VLA source is undetected in the deep ACS images down to $i_{775} = 28.4$ mag. However GOODS 850-5 is detected at low significance in Spitzer IRAC measurements at the few μJy level (Pope et al. 2006) as summarized in Table 2. The source is also detected at

24 μm (Table 2) but undetected both at MIPS 70 μm and 160 μm at a 3σ level ($S_{70\mu\text{m}} < 2.0\text{ mJy}$ and $S_{160\mu\text{m}} < 15.0\text{ mJy}$). However, due to the large beam size ($18''$ at 70 μm and $40''$ at 160 μm) our source would be confused with other objects within the beam. We conclude that the IRAC counterpart presented in Pope et al. (2006) is the proper counterpart of MM J123633+6214.1³.

Due to the lack of a spectroscopic identification, we apply several photometric redshift estimators focusing on different parts of the SED in order to put constraints on the possible redshift–range of the source. Applying the radio/(sub)millimeter index (Carilli & Yun 1999, 2000) on the PdBI flux and the radio flux we estimate a redshift $z = 3.81^{+2.04}_{-1.25}$. Furthermore, we use the infrared galaxy SED templates from Chary & Elbaz (2001) to fit the SED of our source (using the MIPS 24 μm , SCUBA, PdBI and VLA flux) and this method proposes a redshift of $z \sim 3.3 \pm 1.0$, — within the errors consistent with the radio/(sub)mm spectral index estimates — and infrared luminosity $L_{IR} \sim 1 \times 10^{13} L_{\odot}$. We obtain the same result by only using the MIPS 24 μm and the VLA flux. The use of the 850/1.2 mm ratio as a proper redshift indicator is very limited (see Fig. 13 in Greve et al. 2004). However, the SCUBA to PdBI flux ratio of 2.6 limits the possible redshift range from $z \sim 0 - 4$ (see plot in Greve et al. 2004). As Wang et al. (2007) we have also applied the widely used photometric redshift code *hyperz* (Bolzonella et al. 2000) on the optical/near-infrared data from ACS and IRAC. Our redshift estimates give a redshift $z \sim 6$, i.e. consistent with the range of values proposed by Wang et al. (2007). However, we note that with this method only the stellar component of the source is fitted and the applied templates do not reflect the characteristic properties of infrared galaxies.

Assuming a redshift $z \sim 4$, taking into account the optical/near-IR measurements from ACS/Spitzer and applying the reddening law by Calzetti et al. (2000) we estimate the extinction to be $A_V \sim 3$. For comparison, Smail et al. (2004) and Swinbank et al. (2004) derived for SMG samples mean reddening of $A_V \sim 1.70$ and 3.0 , based on optical/near-IR colors.

The source is undetected both in the soft (0.5-2 keV) and hard (2-8 keV) bands in the 2 Ms Chandra observations of GOODS North (e.g., Alexander et al. 2003). However, the lack of X-ray detection cannot exclude the presence of an heavily obscured AGN in GOODS 850-5. Using IRAC, Ivison et al. (2004) proposed a diagnostic tool in order to distinguish between AGN and starburst as dominating energy source. Applying this tool on MM J123633+6214.1 would propose an AGN at redshift $z \sim 2$. However, we note that

³The IRAC and MIPS 24 μm fluxes by Pope et al. (2006) are consistent within 1.5σ with the measurements reported by Wang et al. (2007)

Lacy et al. (2004) and Stern et al. (2005) pointed out that starbursts at $z \sim 4$ contaminate the IRAC selection for $z \sim 1 - 2$ AGNs.

Using either the template fitting from Chary & Elbaz (2001) (resulting in an infrared luminosity $L_{IR} \sim 1 \times 10^{13} L_{\odot}$ and taking into account the conversion between infrared luminosity L_{IR} and SFR (Kennicutt 1998)), we derive a star formation rate $SFR \approx 1800 M_{\odot} yr^{-1}$. By simply using the PdBI flux of 5.0 mJy at 1.25 mm we obtain a star formation rate $SFR \approx 2200 M_{\odot} yr^{-1}$ (Bertoldi et al. 2003). This is consistent with the SFR derived from the radio flux for a source at $z \sim 4$ of $SFR \approx 2000 M_{\odot} yr^{-1}$ (see discussion in Ivison et al. 2002).

We conclude that the multi-wavelength data suggests that MM J123633+6314 is a starburst at $z \sim 4$.

3.2. Radio Faint SMGs in GOODS North

A total of 21 SMGs in GOODS North are securely identified (Pope et al. 2006). In addition to MM J123633+6214.1 there are four SMGs that have even fainter VLA 20 cm fluxes ($\leq 33 \mu\text{Jy}$) than our source. Similar to the counterpart of MM J123633+6214.1 none of them has an ACS counterpart and their IRAC fluxes are faint ($\leq 20 \mu\text{Jy}$). One of these SMGs is the well-studied source HDF850.1 (Hughes et al. 1998; Downes et al. 1999; Dunlop et al. 2004) which is one of the excellent candidates to lie at $z \sim 4$ or higher. To summarize, about 20% of securely identified SMGs could lie at high redshift $z \sim 4$ or higher. Dannerbauer et al. (2002, 2004) and Younger et al. (2007) also reported the discovery of reliable candidates of redshift $z \sim 4$ or higher in other deep fields.

4. Conclusion

We have used the IRAM Plateau de Bure Interferometer to obtain an accurate position and flux at 1.3 mm wavelengths of the SMG MM J123633+6214.1 alias GOODS 850-5 ($S_{1.25 \text{ mm}} = 5.0 \pm 1.0 \text{ mJy}$). This source is coincident with a source detected in deep VLA radio continuum observations at high significance ($S_{1.4 \text{ GHz}} = 32.7 \pm 4.3 \mu\text{Jy}$). The source has also been detected by recent observations obtained at the SMA (Wang et al. 2007) and by Spitzer (Pope et al. 2006) in the IRAC and 24 μm bands. The photometric redshift indicators using the MIR- and FIR SED of MM J123633+6214.1 all point towards a redshift of $z \sim 4$. Based on our millimeter and radio detection, we consider a much higher redshift ($z \sim 6$, as proposed by Wang et al. 2007) unlikely. However, only future facilities with

wide mm-receivers planned e.g. the upgraded PdBI or the LMT will unambiguously solve the question of the true redshift of GOODS 850-5 (ALMA will unfortunately not be able to reach GOODS North). In any case, GOODS 850-5 represent one of the few solid candidates of a high- z ($z > 3$) SMG that contribute to the cosmic SFRD at early cosmic times.

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Facilities: IRAM:Interferometer, VLA, HST (ACS), Spitzer (IRAC, MIPS), CXO (ACIS).

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Table 1: Positions of the SMG MM J123633+6214.1 alias GOODS 850-5

ID	Instrument	R.A. (J2000.0)	Decl. (J2000.0)	Offset $\Delta PdBI - Other$	Reference
MM J123633+6214.1	PdBI	12:36:33.45 \pm 0.04	62:14:08.95 \pm 0.3	—	this paper
VLA Counterpart	VLA	12:36:33.42 \pm 0.01	62:14:08.70 \pm 0.1	0.33''	this paper
GOODS 850-5	SMA	12:36:33.45 \pm 0.03	62:14:08.65 \pm 0.2	0.30''	Wang et al. (2007)
GOODS 850-5	SCUBA	12:36:33.45 \pm 0.73	62:14:09.43 \pm 5.1	0.48''	Wang et al. (2004)
GN 10 (SMMJ123633.8+621408)	SCUBA	12:36:33.8 \pm 1.14 $^{\diamond}$	62:14:08 \pm 8.0 $^{\diamond}$	2.63''	Pope et al. (2005)

Note. — Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

$^{\diamond}$ The given position uncertainty is the search radius for counterparts of 8'' applied by Pope et al. (2006).

Table 2: Fluxes of the SMG MM J123633+6214.1 alias GOODS 850-5

Band (1)	Unit (2)	MM J123633+6214.1 (3)	Instruments (4)	Reference (5)
$X - Ray_{0.5-2 \text{ keV}}$	$10^{-17} \text{ ergs cm}^{-2} \text{ s}^{-1}$	<2.5	Chandra	Alexander et al. (2003)
$X - Ray_{2-8 \text{ keV}}$	$10^{-16} \text{ ergs cm}^{-2} \text{ s}^{-1}$	<1.4	Chandra	Alexander et al. (2003)
B_{435}	mag	>29.1	ACS	Giavalisco et al. (2004)
V_{606}	mag	>29.1	ACS	Giavalisco et al. (2004)
i_{775}	mag	>28.4	ACS	Pope et al. (2006)
z_{850}	mag	>27.9	ACS	Giavalisco et al. (2004)
$S_{3.6 \mu m}$	μJy	1.21 ± 0.39	IRAC	Pope et al. (2006)
$S_{4.5 \mu m}$	μJy	1.96 ± 0.36	IRAC	Pope et al. (2006)
$S_{5.8 \mu m}$	μJy	2.72 ± 0.88	IRAC	Pope et al. (2006)
$S_{8.0 \mu m}$	μJy	5.11 ± 1.14	IRAC	Pope et al. (2006)
$S_{24.0 \mu m}$	μJy	30.7 ± 5.4	MIPS	Pope et al. (2006)
$S_{70 \mu m}$	mJy	<2.0	MIPS	Huynh et al. (2007); Frayer et al. (2007)
$S_{160 \mu m}$	mJy	<15.0	MIPS	Huynh et al. (2007); Frayer et al. (2007)
$S_{850 \mu m} - Wang04$	mJy	12.94 ± 2.14	SCUBA	Wang et al. (2004)
$S_{850 \mu m} - Pope06$	mJy	11.3 ± 1.6	SCUBA	Pope et al. (2006)
$S_{870 \mu m}$	mJy	12.0 ± 1.4	SMA	Wang et al. (2007)
$S_{1.25 \text{ mm}}$	mJy	5.0 ± 1.0	PdBI	this paper
$S_{1.4 \text{ GHz}}$	μJy	32.7 ± 4.3	VLA	this paper

Note. — Col. (1): Band in which flux is measured. Col. (2): Units of the flux density measurements. Limits are 3σ . Optical/near-IR magnitudes are measured in a $0.2''$ diameter aperture and are on the AB system (Oke & Gunn 1983), see also Giavalisco et al. (2004). IRAC fluxes are measured in a $4''$ diameter aperture. MIPS $24 \mu m$ flux is measured within a $5.7''$ aperture. For the MIPS 70 and $160 \mu m$ a $18.5''$ and $40.0''$ aperture were used. (3): Measurements for the SMG MM J123633+6214.1. Col. (4): Instruments. Col. (5): References.

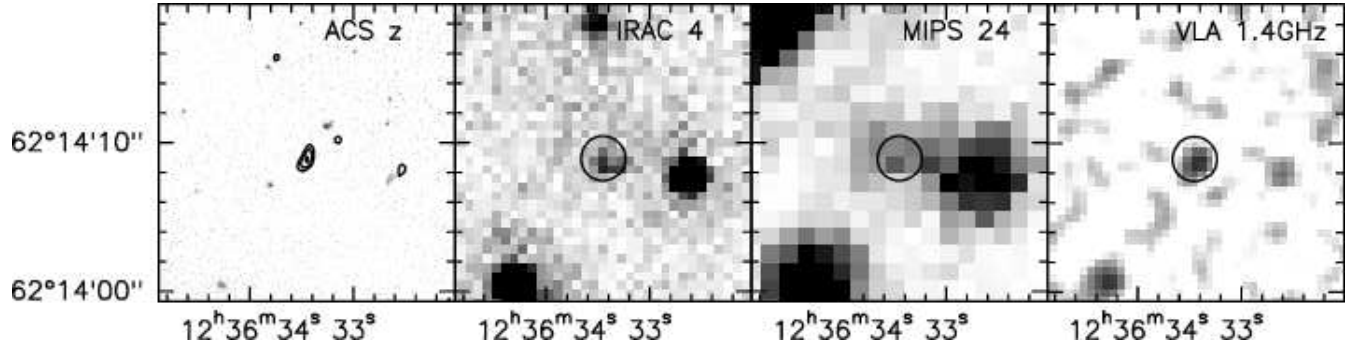


Fig. 1.— $20'' \times 20''$ ACS z_{850} , IRAC $8.0 \mu\text{m}$, MIPS $24 \mu\text{m}$ and radio images of the field of MM J123633+6214.1. PdBI contours of 1.25 continuum emission of MM J123633+6214.1 overlaid on the ACS z_{850} image and start at 3σ with steps of 1 mJy. $3.0''$ circles are drawn on the PdBI position in the IRAC $8.0 \mu\text{m}$, MIPS $24 \mu\text{m}$ and radio images.